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Metal multilayer mirrors for EUV wide field telescopes

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ABSTRACT

Metal multilayer mirrors have been designed for the ALEXIS satellite, which is to carry six wide field telescopes to perform an all-sky survey in three or four narrow wavelength bands in the EUV. Comprised of alternating layers of molybdenum and silicon, the mirrors are optimized to provide maximum reflectivity at angles from 11.5 to 17° off normal incidence and at wavelengths of 133, 171, or 186Å. Simultaneously, the mirrors use a "wavetrap" described below to suppress reflectivity at 304Å, where the extremely strong geocoronal line of He II causes severe background problems.

Low reflectivity at 304Å is achieved by superposing two layer pairs that provide destructive interference with an effective $2d$ spacing of 152Å. The Mo layers in this wavetrap must be very thin, about 10Å each, in order to allow the shorter wavelengths desired for peak reflectivity to penetrate without significant attenuation. Because refraction changes the effective angle of passage through the wavetrap, a joint optimization between layer thicknesses in the deep layers and the wavetrap layers must be performed for each target peak wavelength. For the 186Å mirror, the optimum design from substrate upward is 40 layer pairs, each 74Å Si and 31Å Mo, followed by 2 layer pairs, each 55Å Si and 10Å Mo. Calculations predict this design will have a peak reflectivity at 186Å of 35 percent and a 304Å reflectivity less than 10^{-5}, if available optical constants are correct and the multilayer can be fabricated without difficulty. We will present details of the calculations and laboratory measurements of the reflectivity performance attained with prototype mirrors.

1. INTRODUCTION

The ALEXIS satellite[1] is designed to survey the entire sky in several narrow wavelength bands, centered on iron emission lines from hot interstellar plasma[2] and on a band in the continuum of hot stellar objects. It will carry six telescopes using metal multilayer mirrors to focus this cosmic extreme ultraviolet (EUV) light. Consisting of 50 to 100 alternating layers of molybdenum (Mo) and silicon (Si), the multilayers (also called layered synthetic microstructures) reflect EUV light at near normal incidence. Telescopes employing similar multilayer mirrors were recently flown on a rocket flight to observe the solar corona[3]. The ALEXIS multilayers will be vacuum deposited by magnetron sputtering using argon gas. Design of the multilayers is the subject of this paper.

2. CALCULATIONS

Optimizations were performed, with a computer code that uses the solution method of Born and Wolf[4], to determine the layer thicknesses yielding the best compromise of high peak reflectivity and low background reflectivity, as described below. Optical constants were adopted for Mo from Windt[5] and for Si from Palik[6].

Peak reflectivity is obtained approximately by tuning the spacing of the Mo/Si layers until the Bragg condition ($2d \sin\theta = n\lambda$, where d is the total thickness of Mo plus Si in each layer pair, θ is the angle of reflection, n is a positive integer, and λ is the wavelength) is satisfied for the working wavelength with $n = 1$ for the desired angle θ (fixed by the optical design). Further fine tuning is necessary because of refraction and absorption effects.

While maximizing peak reflectivity we must minimize background reflectivity. Our most serious background in low earth orbit will be the geocoronal emission of ionized helium at 304Å. Consisting of resonantly scattered solar line radiation and fluorescence, this radiation is very intense (up to 13 rayleighs), perhaps 10^5 times as strong as the signal we are attempting to measure from interstellar plasma. Therefore we must achieve a rejection ratio of at least 10^6 between 304Å and the peak wavelength for each mirror. Whatever part of this ratio cannot be attained by a ratio of reflectivities at the two wavelengths must be supplied by filtration, which cuts our sensitivity. To solve this problem we have explored two kinds of multilayer structures that minimize reflection of the mirror at 304Å without severely degrading the reflectivity at the peak wavelength.

One design that reduces 304Å reflection simply decreases the thickness of Mo layers while keeping the d-spacing the same. When Mo occupies less than about 20 percent of d, the 304Å reflectivity is reduced to less than 10^{-3}, but unfortunately the peak reflectivity also is reduced to about 70 percent of the attainable maximum.

The second kind of structure employs a "wavetrap", consisting of two layer pairs laid down on top of the other layers. To suppress reflection of 304Å background, the effective $2d$-spacing must be 152Å, so that standing wave patterns are set up that destructively interfere with the reflected wave. The 304Å radiation is then absorbed within the multilayer. Since the standing waves thus set up utilize the deeper Mo layers (i. e., those spaced for the peak reflectivity) as reflectors, determination of the optimum d-spacing and Mo layer thickness in a wavetrap depends on the thicknesses of the deeper layers. We have computed models that have good peak reflectivity and 304Å reflectivities as low as 10^{-6}.

3. LABORATORY APPARATUS

An EUV reflectometer has been constructed at Los Alamos to provide a facility for measurement and testing of multilayer mirrors and for calibration of completed ALEXIS telescope assemblies. The layout, pictured in Fig. 1, consists of a Penning discharge light source (Berkeley Photonics, Inc., Model PDS; interchangeable with a Manson X-ray source) illuminating a Hettrick Scientific "HIREFS 164" monochromator (100-1500Å). Argon gas is excited and sputters aluminum electrodes, producing a line-rich discharge. Helium gas is also used with stainless steel electrodes. The monochromatized EUV beam is channeled through a filter wheel into a reflectometer of standard design in a vacuum chamber with a diameter of 0.9 meter.

Since the Penning discharge output is spontaneously variable, the beam intensity is monitored on 0.3 s intervals by intercepting a part of it with a channeltron detector. The entire procedure of taking data for a rocking curve is automated through a Sun scientific workstation that controls positioning motors and accumulates reflectivity data

4. UNIFORMITY OF LAYERS

A major issue is the uniformity of the sputtered layers, for roughness causes scattering of incident light out of the geometric optical path and thus loss of sensitivity. Our specification for uniformity of d-spacing is 1 percent RMS. Ovonics, Inc. is under contract to fabricate the multilayer mirrors. The majority of effort so far under this contract has been to design shaper bars for the sputtering deposition system that produce layers of this uniformity. Measurements to date on sample mirrors indicate attainment of uniformity of better than 2 percent over a 15-cm circle. Although these samples were not spun during deposition the flight mirrors will be spun to further improve uniformity. The flight mirrors will have a 12.8-cm diameter and a 13.5-cm radius of curvature

5. RESULTS

The wavetrap design for 304A background rejection requires very thin Mo layers, as little as 10A. A sample has been fabricated to verify that layers this thin can be fabricated, consisting of 10 Mo/Si layer pairs each appropriate for the actual wavetrap mirror (which has only two such layer pairs). While Cu Kα diffractometry and Auger electron spectroscopy (AES) confirm a 63A d spacing in this sample, there are significant differences between computed and measured reflectivities at 170A that are not understood

Sample multilayer mirrors fabricated by Ovonics, Inc. to the specifications for the 186A mirrors have been received. Reflectivity curves have been obtained at incident wavelengths of 170, 256, and 304A. The Penning discharge unfortunately does not emit significant flux at 186A

The sample received most recently was designed with the structure (from Si wafer substrate upward): 30 layer pairs, each 24A Si and 31A Mo, followed by 2 layer pairs (the 304A wavetrap), each 55A Si and 10A Mo. This structure is essentially confirmed by Cu Kα diffractometry, but AES performed by Ovonics indicates the presence of substantial carbon and oxygen near the front surface. Our own measurements, described below, corroborate this. It should be expected that either Si or Mo will oxidize to some degree when the mirror is exposed to air, but the presence of carbon is currently unexplained. It may have accumulated during deposition or handling

Measurements of EUV reflectivity of this mirror in our facility are shown in Fig. 2, together with some models computed in an attempt to fit the data. A model for the target design is shown as dotted lines in each panel. Laboratory data at 170Å indicate that the deep layers are behaving almost as predicted by the computations, generating a peak reflectivity of about 0.30, somewhat less than the 0.35 predicted for a pure Mo/Si structure. However, the data at 304Å indicate that the wavetrap is not operating as expected.

In view of the presence of carbon and oxygen in the AES data, a "contaminated" model was computed with the structure above, modified only in the wavetrap, as follows. Instead of 2 layer pairs as designed, assume 1 clean layer pair of 55Å Si and 10Å Mo, then 45Å Si, 10Å SiO, 10Å Mo (probably Mo oxide, but we have no optical constants for that), and 35Å C as the front surface. As shown in Fig. 2, this model fits the laboratory measurements much better than the intended "clean" model. Optical constants for SiO were adopted from Windt[5], since he comments that his sample, intended to be Si, appears similar to Si oxide. Approximate agreement between this model and the data reassure us that the adopted optical constants for the sputtered materials are reasonably realistic, eliminating one explanation for some failures to fit our laboratory data. The discrepancy between fit and data for the 10-layer wavetrap remains.

We conclude that some oxidation of the front layer(s) of multilayer mirrors is unavoidable with normal handling. However, since carbon on the multilayer substantially degrades the peak reflectivity performance, we intend to eliminate it. Should this not prove possible, we have designed a "dirty" wavetrap that uses the carbon layer instead of a top Mo layer to recover the very low reflectivity required at 304Å. This "dirty" wavetrap mirror cannot have as high a peak reflectivity at the working wavelength, because carbon is very absorptive there. Nevertheless, the sensitivity of ALEXIS depends on reflectivities at both the working wavelength and at 304Å, and the "dirty" wavetrap may prove the most sensitive feasible design.

Measurements and calculations are continuing. Additional prototypes will be produced by Ovonics before multilayers are deposited on the quartz flight substrates.

6. ACKNOWLEDGEMENTS

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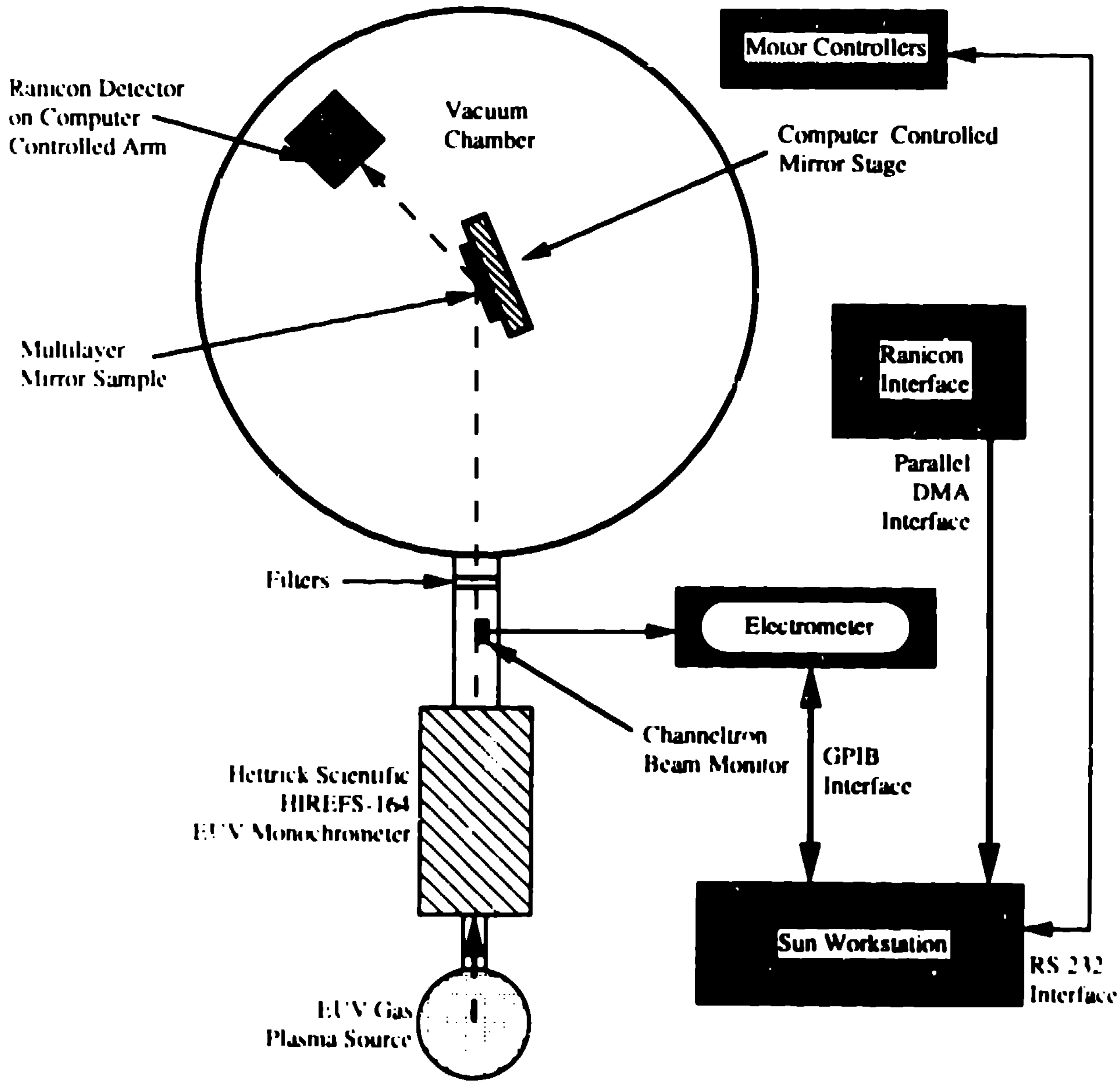

Figure 1 Block diagram for the system used to obtain EUV reflectivity data for this paper

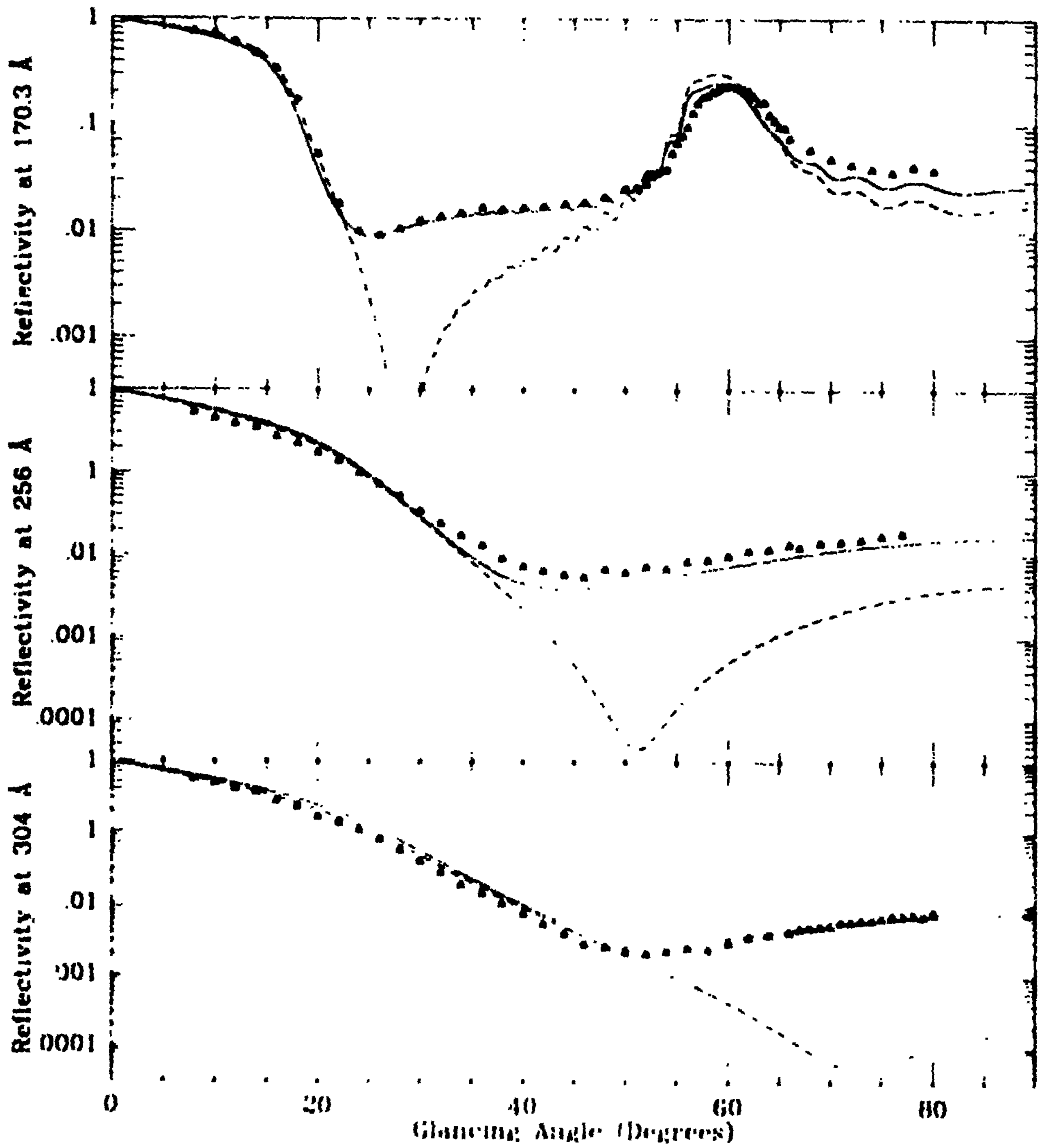

Figure 2 Comparison of reflectivity data for a sample mirror and models with (solid line) and without (dotted line) surface contamination by carbon and oxygen. The contaminated model has an extra 35 Å of carbon on the front surface, and the top 10 Å of the topmost silicon layer is oxidized. See text for exact description of the models.